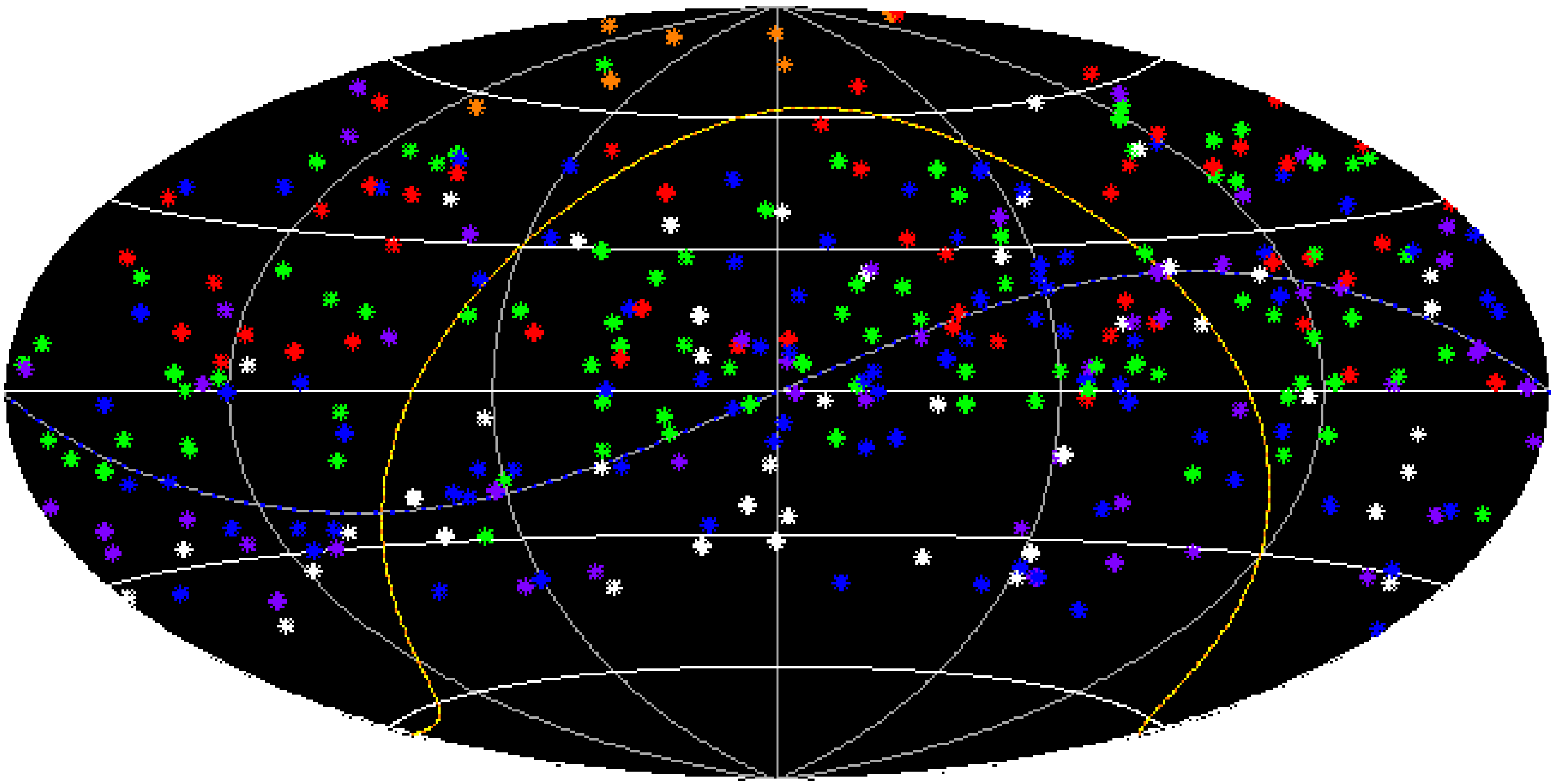
Extending the ICRF to Higher Radio Frequencies: X/Ka (8.4/32 GHz) Global Astrometry



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JPL/Caltech/NASA

24-25 March 2009

Outline

- Motivation for a radio frame above 8 GHz
- Overview of current radio frames
- Game plan to create celestial frames > 8 GHz
- Observations and Results
- Accuracy: X/Ka vs. S/X
- Plans to reduce error budget

Motivation

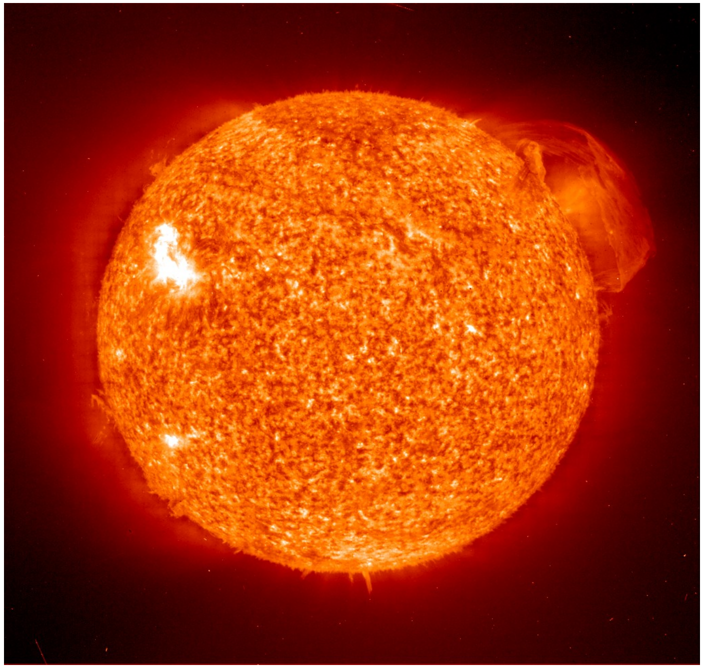
- **Astrometry, Geodesy and Deep Space navigation, now at 8.4 GHz (X-band) with 2.3 GHz (S-band) plasma calibrations**

Going to Higher radio frequencies allows

- **Potentially more *compact* sources**
  Potentially more *stable* positions
- **Higher Telemetry Rates to Spacecraft**
- **Avoid 2.3 GHz *RFI* issues**
- **Ionosphere & solar plasma down 15X !! at 32 GHz (Ka-band) compared to 8 GHz.**

Drawbacks of Higher radio frequencies:

- **More weather sensitive**
- **Weaker sources, shorter coherence times**
- **Many sources resolved**
- **Antenna Pointing more difficult**



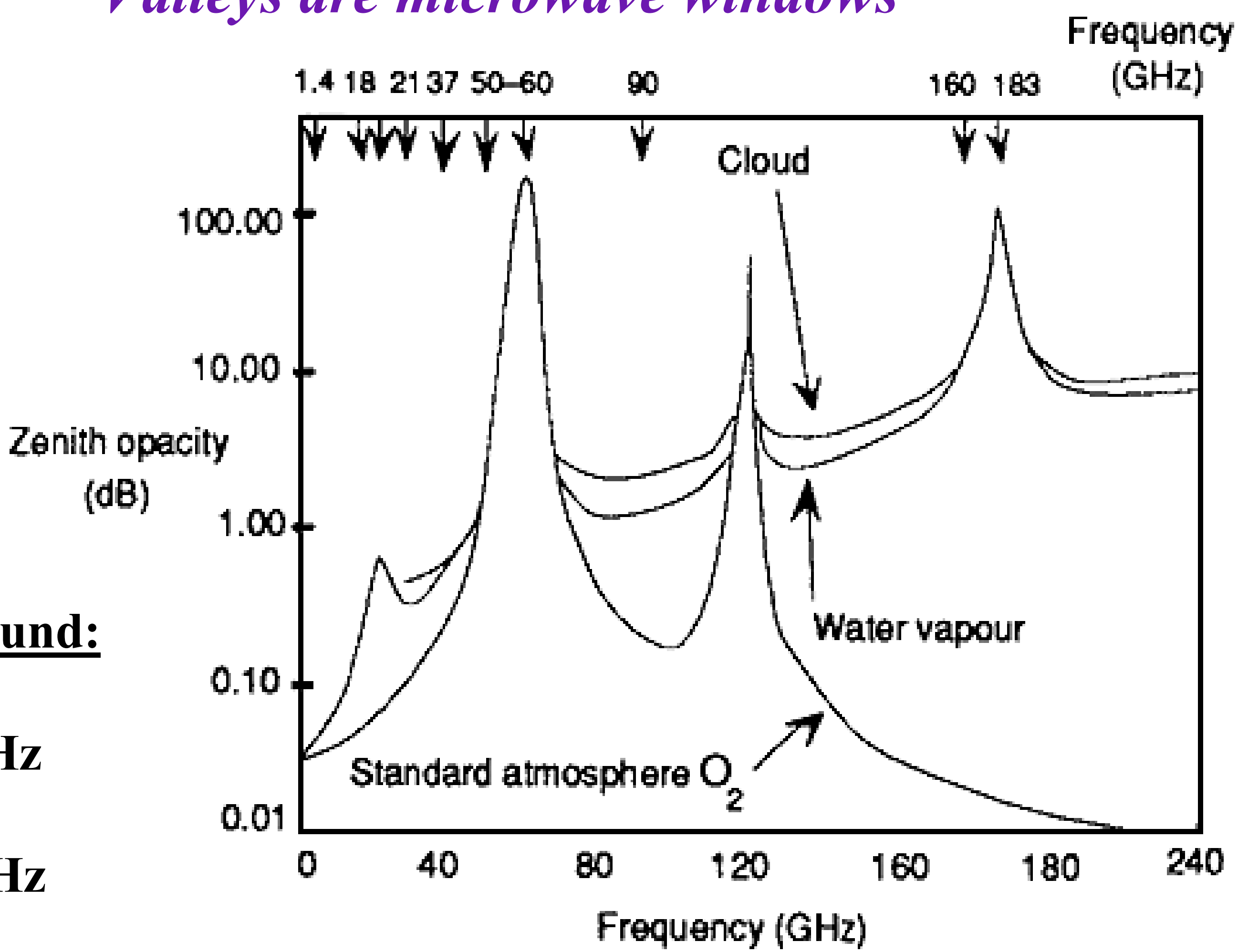
Picture credit: SOHO/ESA/NASA

The Atmosphere Effects Sensitivity

The three curves show absorption in a dry atmosphere, in the same atmosphere with 20 kg/m2 of added water vapour, and with both water vapour and 0.2 kg/m2 of stratus cloud added.

Murphy, R. et al., 1987,
- Earth Observing System Volume IIe: HMRR High-Resolution Multifrequency Microwave Radiometer. Published by NASA, Goddard Space Flight Centre, Greenbelt, Maryland 20771

Valleys are microwave windows



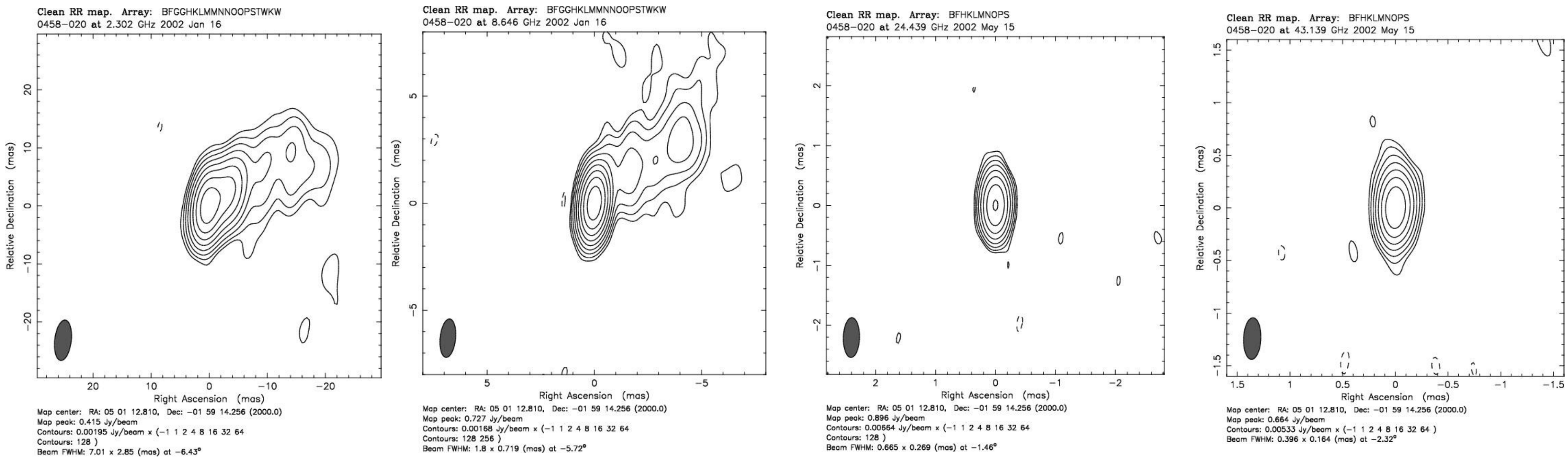
Atmosphere Background:

3K/atmo @ 8 GHz

10-15K/atmo @32 GHz

Murphy, R. et al., 1987, Earth Observing System Volume IIe: HMRR High-Resolution Multifrequency Microwave Radiometer. Published by NASA, Goddard Space Flight Centre, Greenbelt, Maryland 20771, USA, 59pp.

Source Structure vs. Frequency



S-band
2.3 GHz
13.6cm

X-band
8.6 GHz
3.6cm

K-band
24 GHz
1.2cm

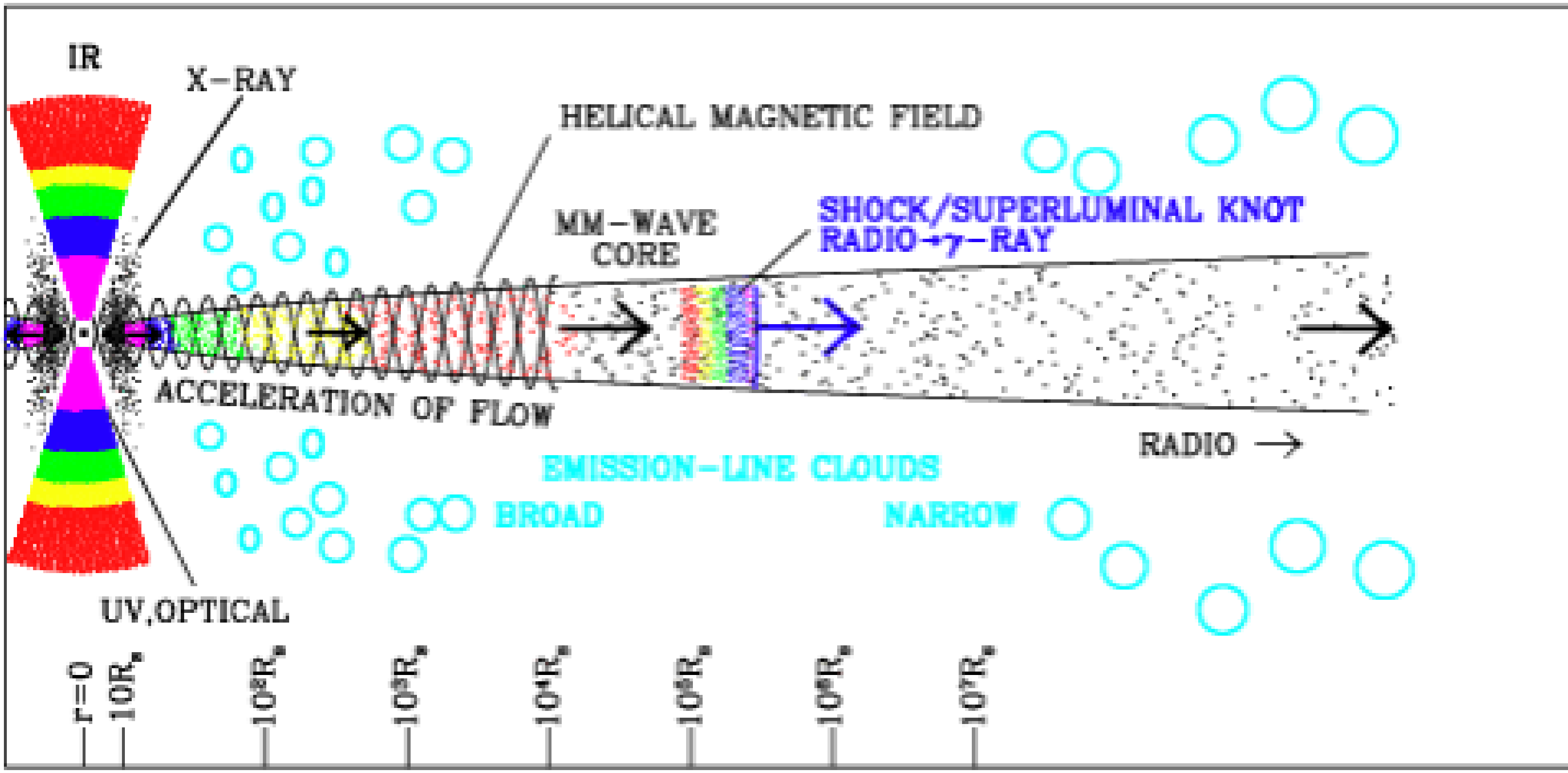
Q-band
43 GHz
0.7cm

Ka-band
32 GHz
0.9cm

The sources become better ----->

Image credit: P. Charlot, Bordeaux Observatory & KQ VLBI Collaboration

Features of AGN (*from Marscher*)

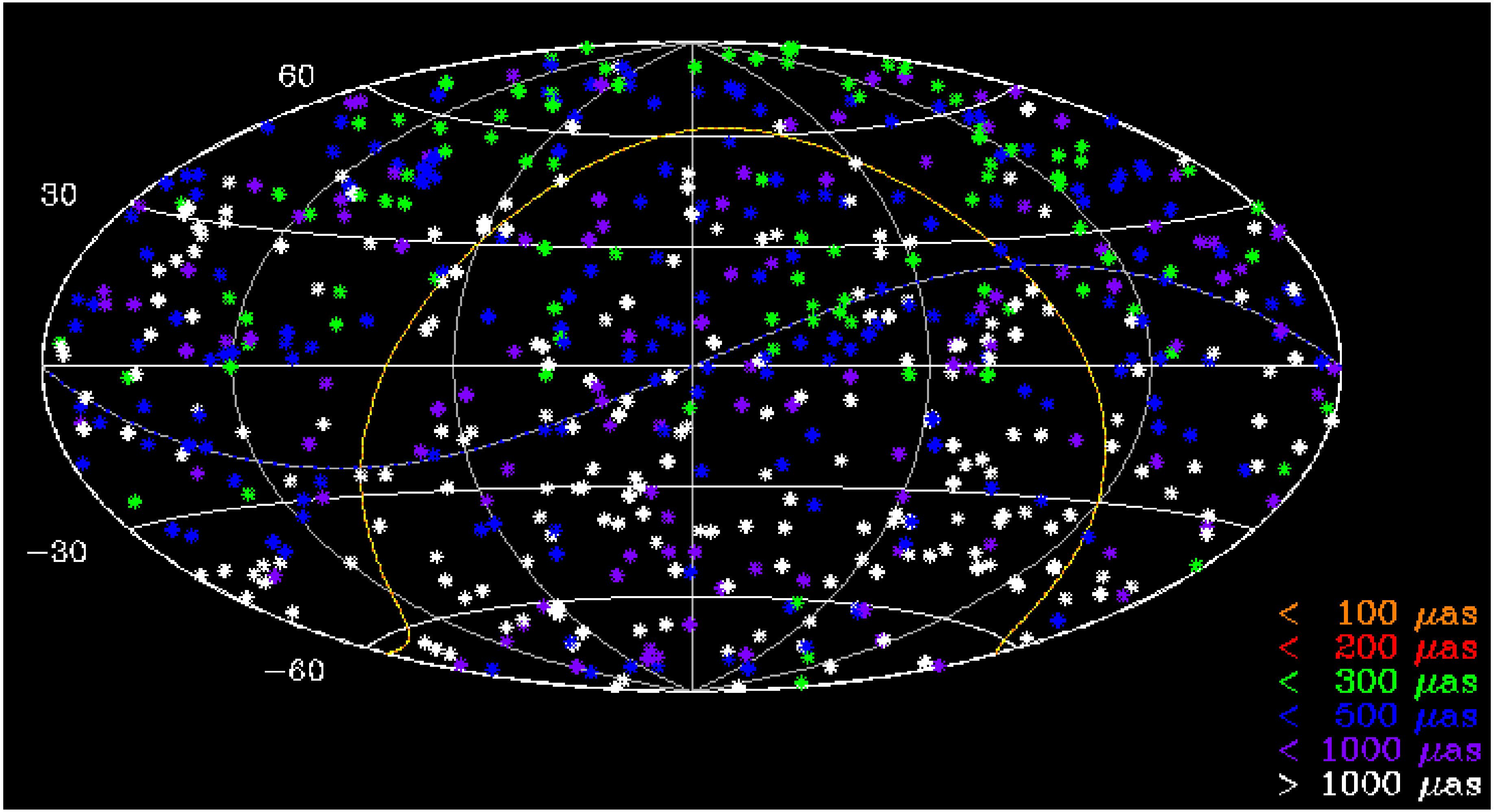


Features of AGN: *Note the Logarithmic length scale.*

"Shock waves are frequency stratified, with highest synchrotron frequencies emitted only close to the shock front where electrons are energized. The part of the jet interior to the mm-wave core is opaque at cm wavelengths. At this point, it is not clear whether substantial emission occurs between the base of the jet and the mm-wave core."

Credit: Alan Marscher, `Relativistic Jets in Active Galactic Nuclei and their relationship to the Central Engine,' Proc. of Science,VI Microquasar Workshop: Microquasars & Beyond, Societa del Casino, Como, Italy, 18-22 Sep 2006.

S/X (2/8 GHz) ICRF: 608 Sources

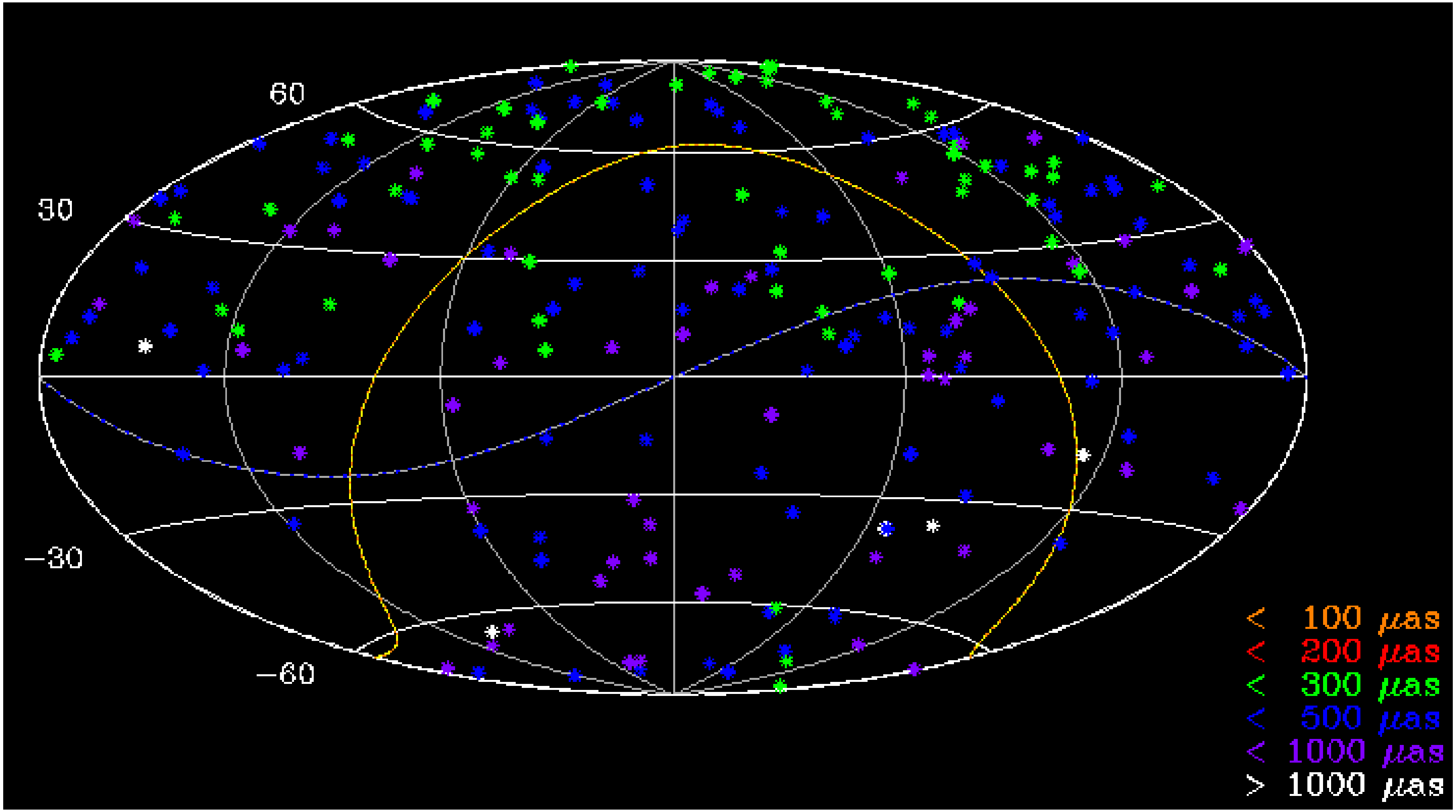


608 sources from S/X data up to 1995

Errors Inflated: scale plus 250 μas RSS'ed

Credit: *Ma et al, AJ, v. 116, 516, 1998.*

S/X Defining: 212 Sources

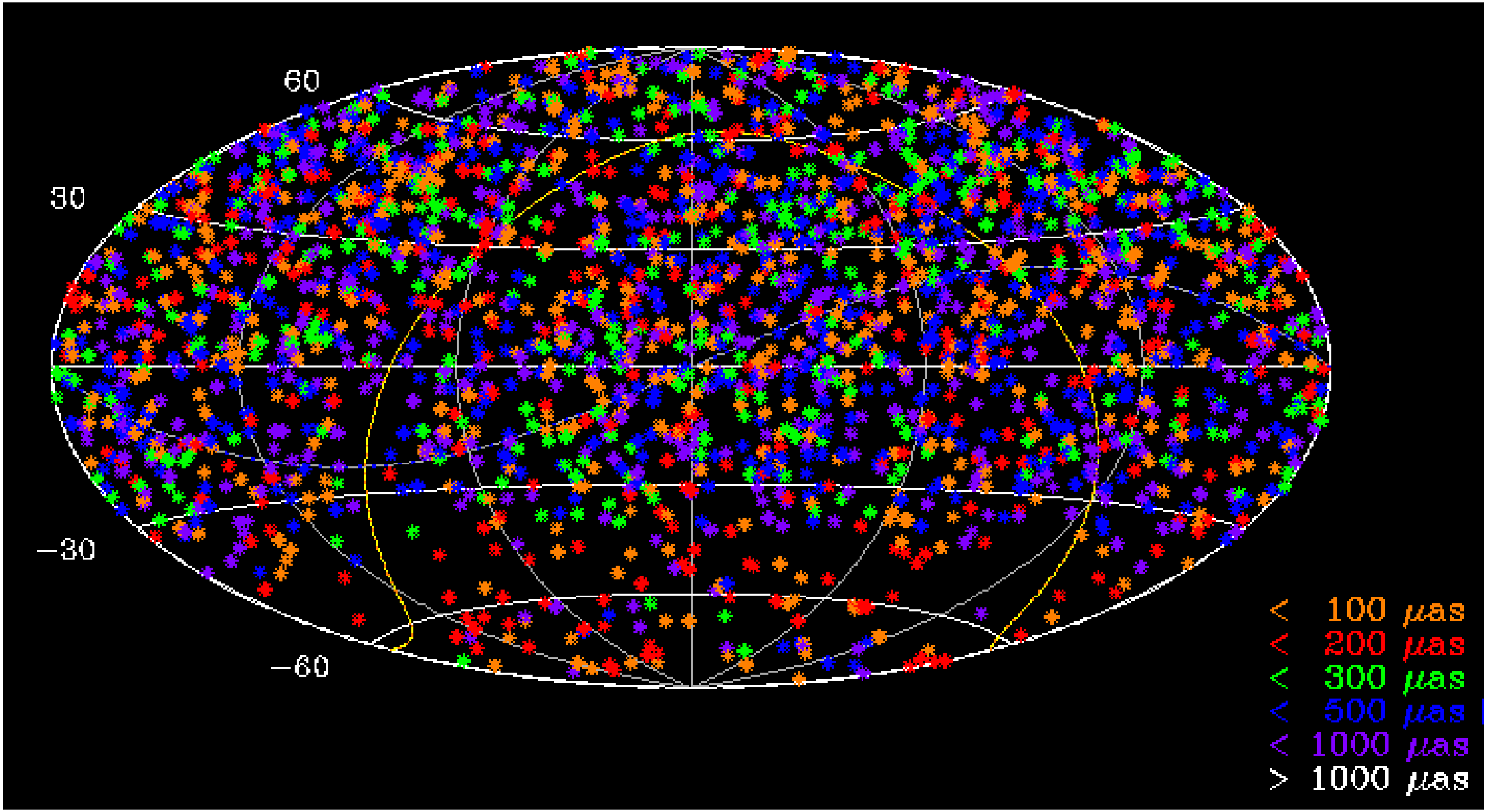


212 “**Defining**” sources determine conventional rotation

Errors scaled plus 250 µas RSS’ed

Credit: *Ma et al, AJ, v. 116, 516, 1998.*

S/X-band (2/8 GHz): 3500* Sources

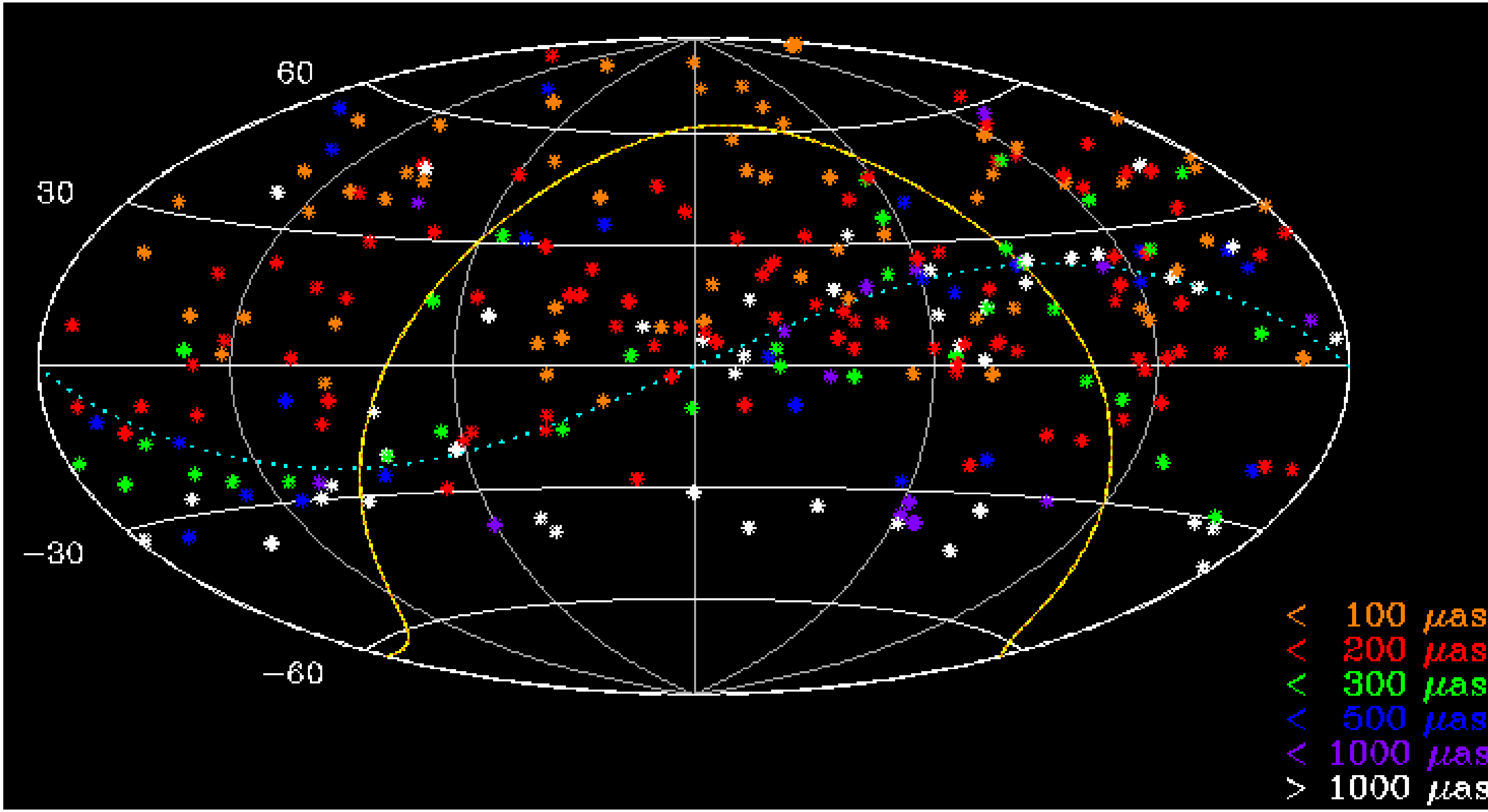


*Plotted ~2400 sources with Declination uncertainty < 1 mas

GSFC-2008b-astro data to June 2008 (some K-band [22 GHz] data)

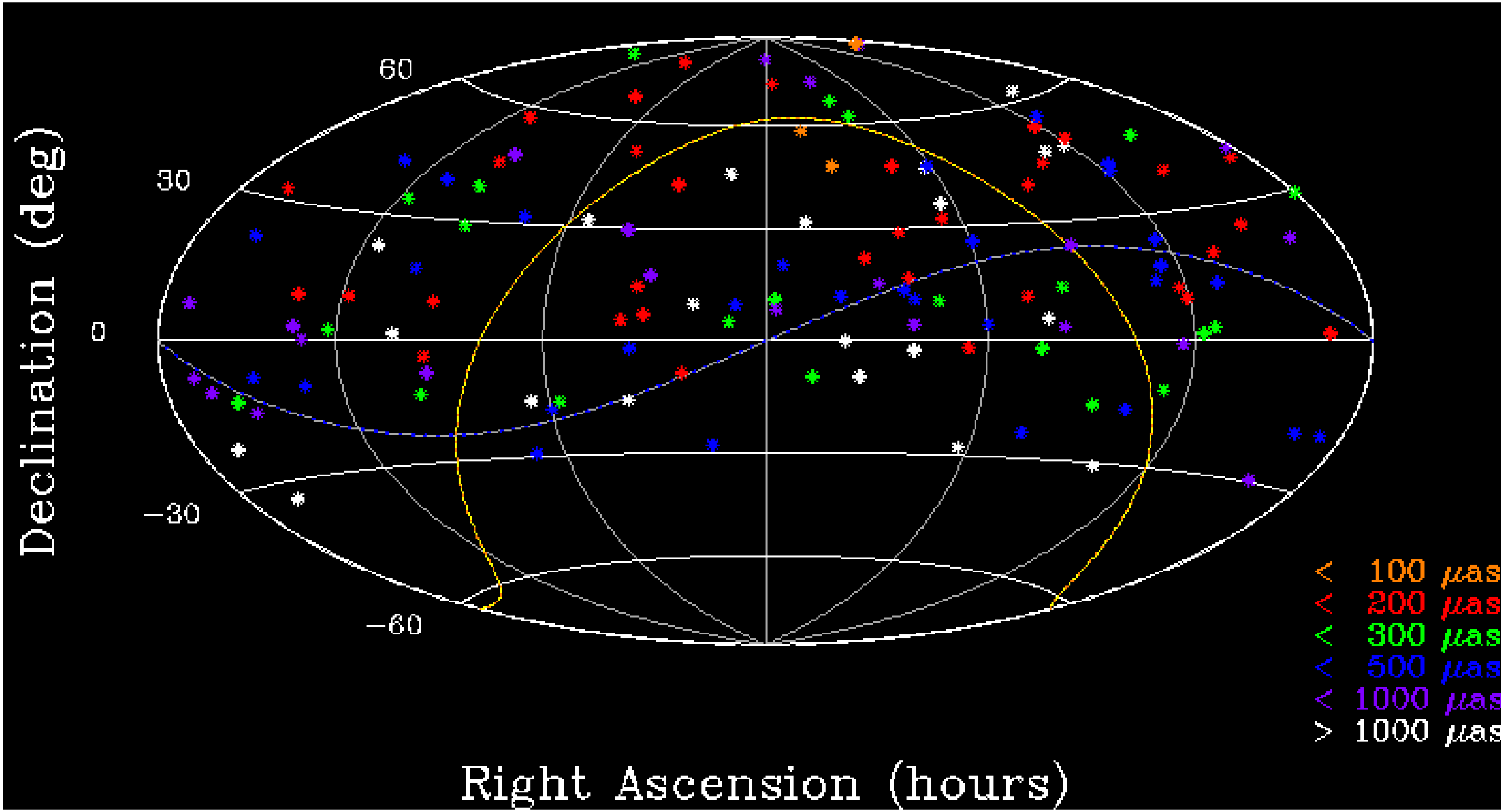
Credit: *Petrov, Kovalev, Fomalont, & Gordon, VCS-6, AJ, 2008, 136, 580.*

K-band (24 GHz): 275 Sources



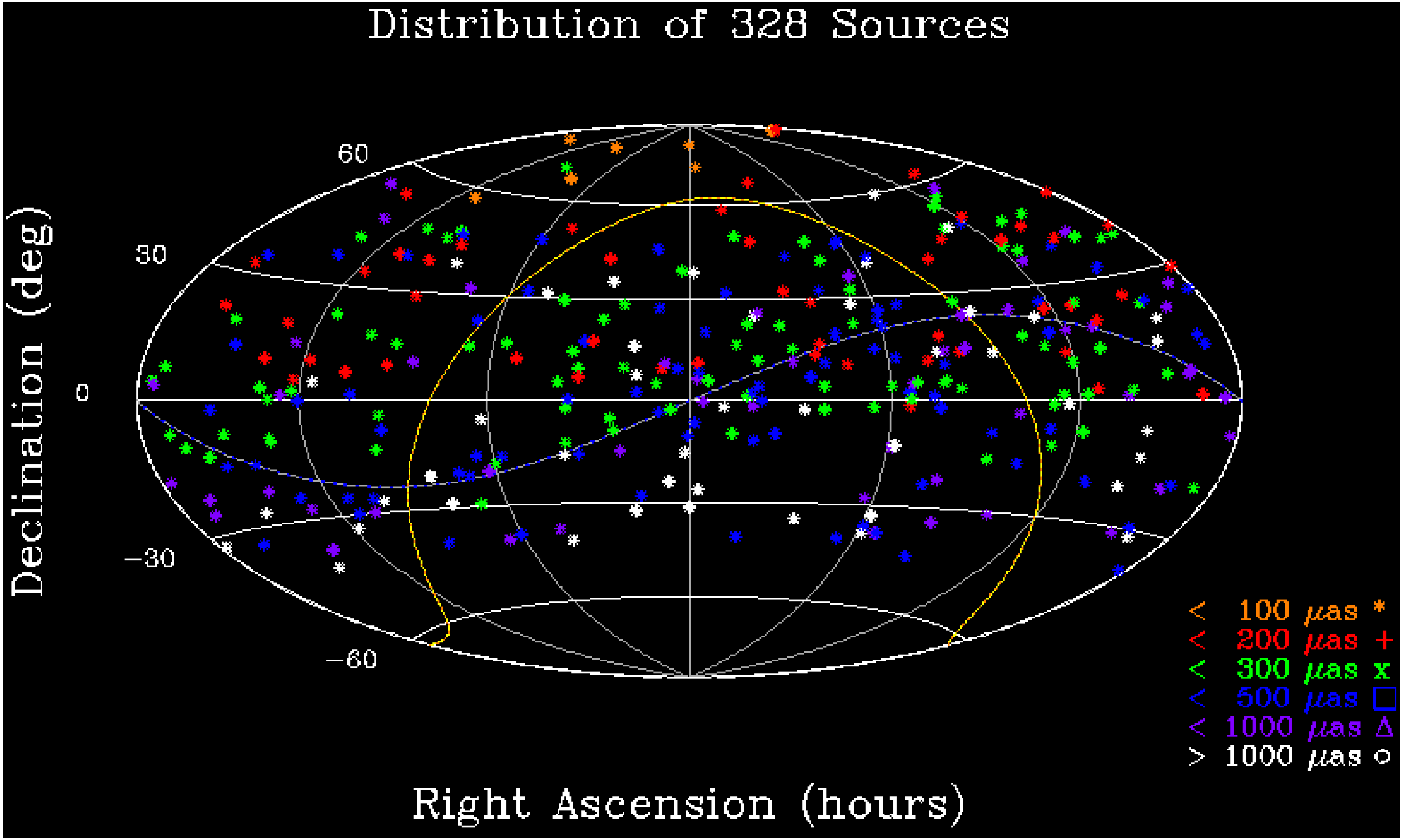
VLBA Data 10 sessions 2002-07
Formal errors with no inflation
Credit: *G.E. Lanyi et al, IVS meeting 2008, St. Petersburg*

Q-band (43 GHz): 132 Sources



VLBA Data 4 sessions 2002-03
Formal errors with no inflation
Credit: *G.E. Lanyi et al, AJ, submitted Nov 2008*

X/Ka (8.4/32 GHz): 328 Sources



DSN data 2005-09, Dec down to - 45 deg

Phase II: *X/Ka bigger Antennas, Baselines*

- **Phase I -** Until 32 GHz available, bracket with VLBA's closest bands
  24 GHz (K-band)
  43 GHz (Q-band)
  - Interpolate behavior to 32 GHz (Ka-band)
  - identifies likely detectable sources at Ka
  - maps sources to provide structure information

- **Phase II -** 32 GHz and 8.4 GHz (Ka/X-band) DSN observations
  34m Beam-waveguide antennas, 2 baselines:
  Goldstone California to
  Madrid, Spain 8,400 km
  Tidbinbilla, Australia 10,500 km

- **Phase III** - *Add more antennas to the network*
  - *VLBA: 32 GHz proposal not funded at this time*
  - *Other sites have Ka, but none with X/Ka to calibrate plasma*

X/Ka Observations

Deep Space Network 34m Beam-waveguide antennas

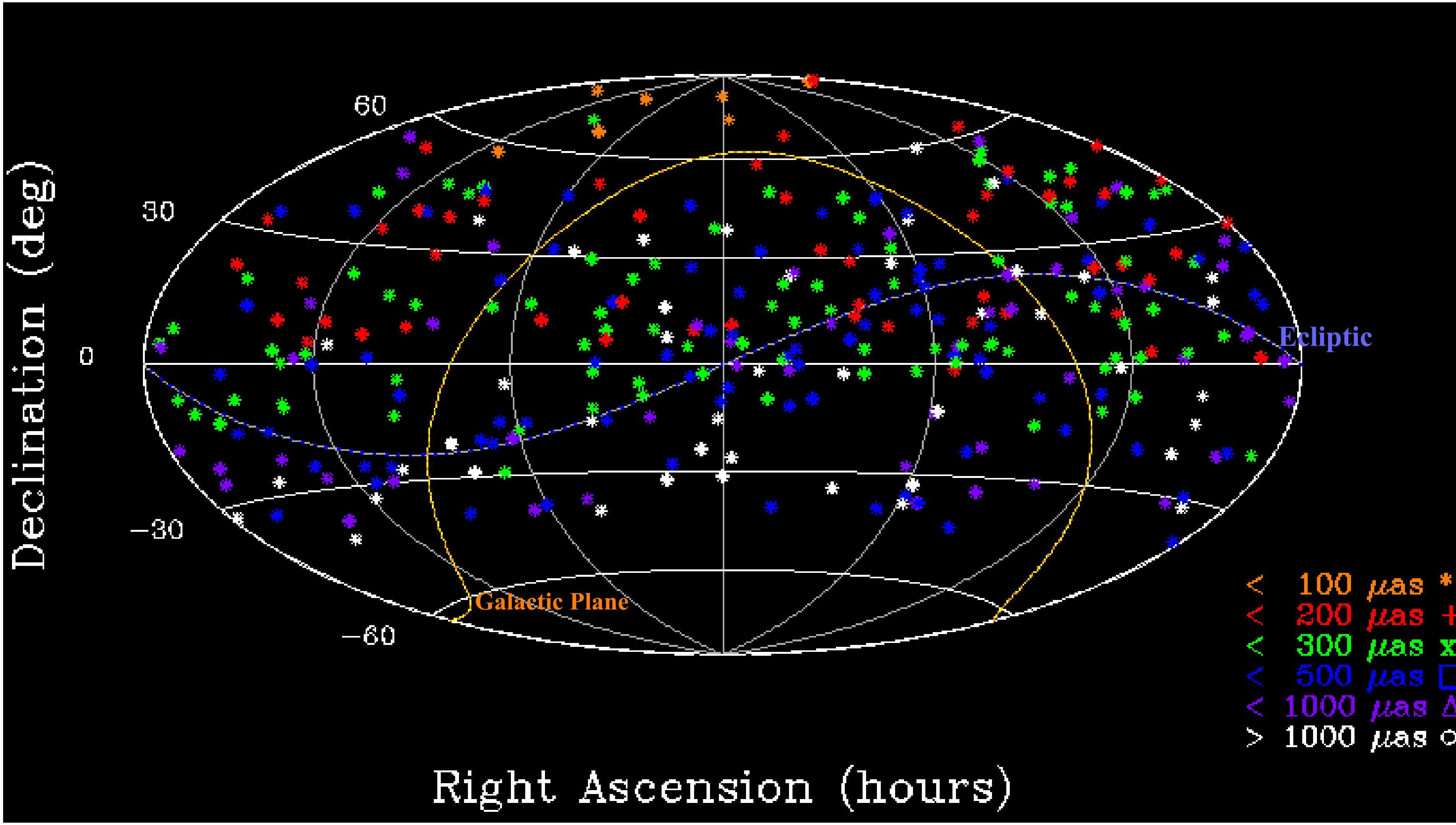
- 41 sessions, 8536 delays/rates, 1580 parameters
  very small data set by S/X standards of 5 x 10^6 delays
- nominally 24 hours each to cover full range of RA
- Record rate: now 112 Mbps (MkIV mode A)
  future 896 Mbps (Mk5-A) = 3X sensitivity
- 360 MHz spanned bandwidth (receiver 500 MHz, VC limited)
- 1-2 snapshots, ~2 min each

Reference Frame Modelling

X/Ka cannot achieve the results which follow without S/X models! Thus, we cannot get rid of S/X for years to come!

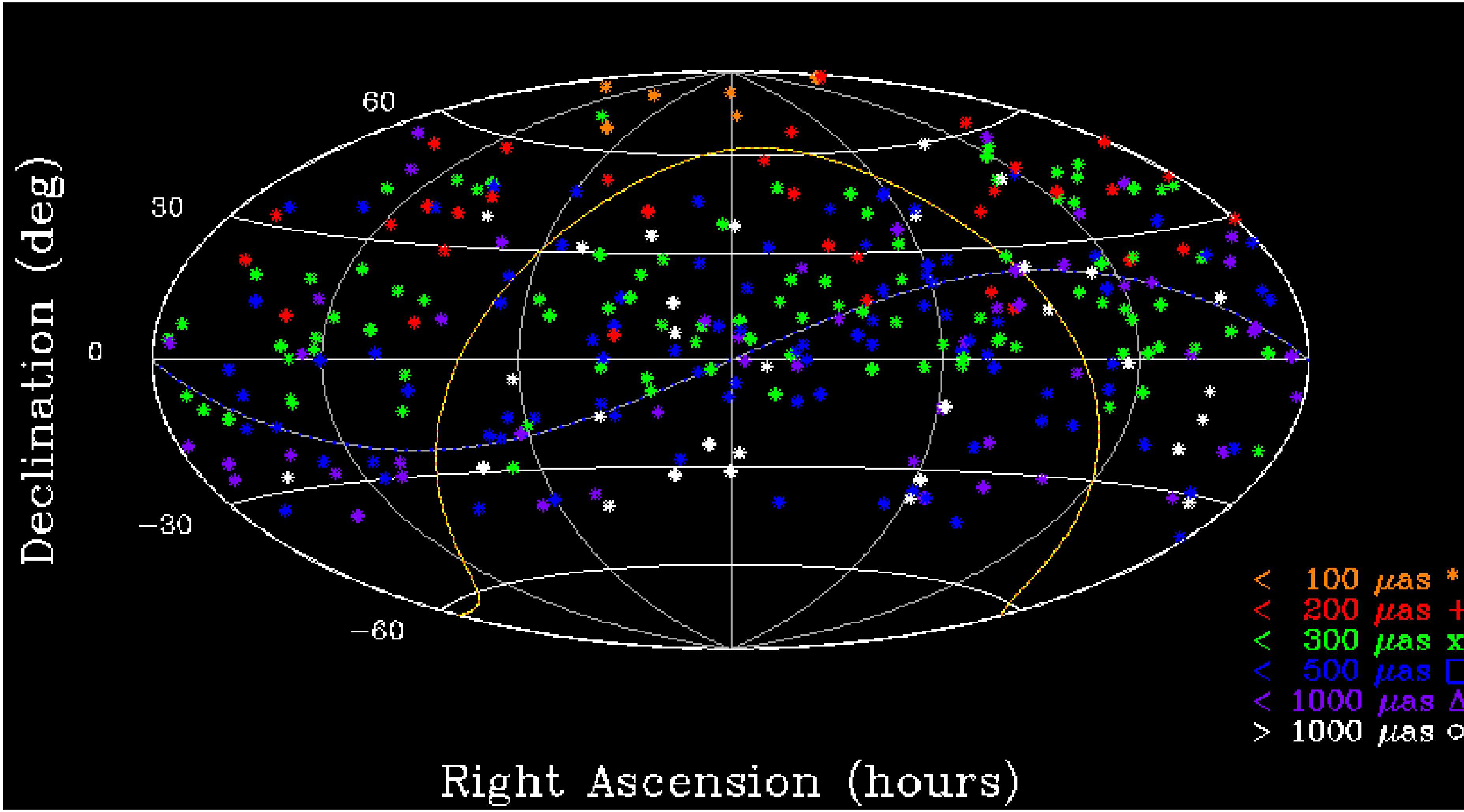
- Rotational alignment set to **S/X** ICRF
- Nutations: MHB model tuned to **S/X** VLBI
- Tidal models tuned to fit **S/X** VLBI
- UTPM: GPS + **S/X** VLBI data

X/Ka results: 328 Sources detected



DSN data 2005-09 Dec to - 45 deg

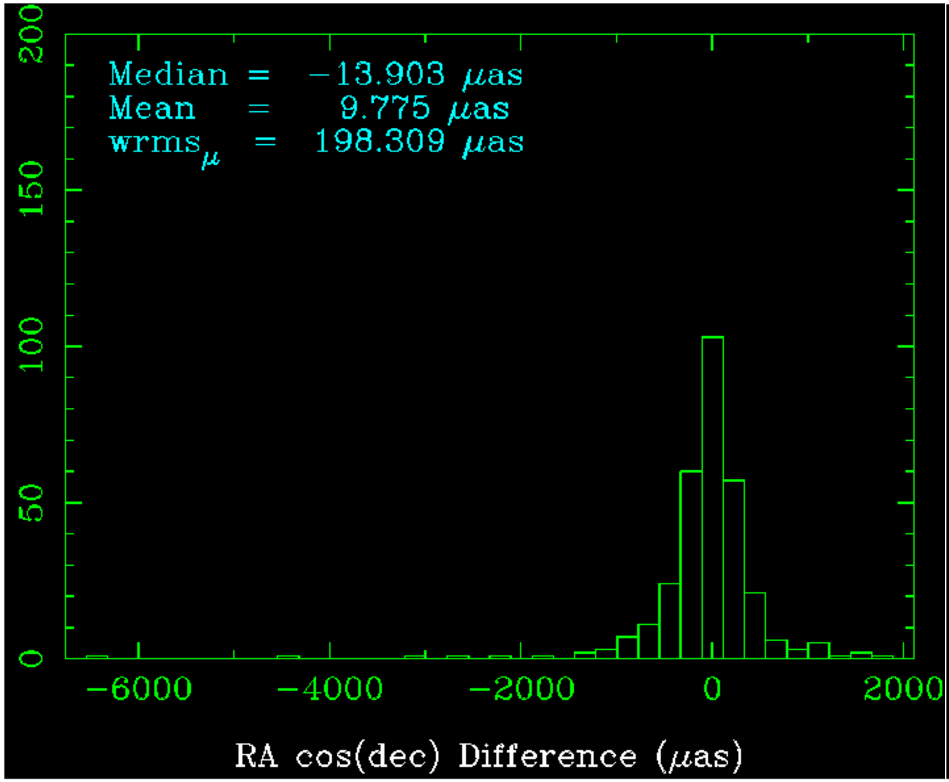
X/Ka *vs.* S/X

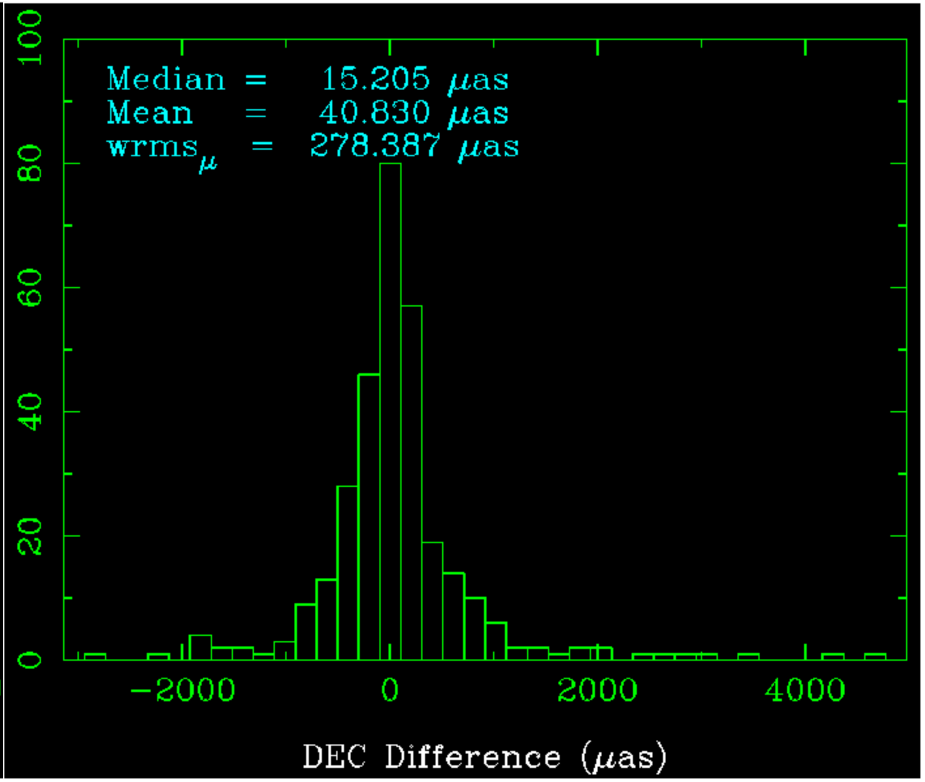


312 common sources--at least 2 group delays, < 5mas sigma

ΔRA, Δ Dec: X/Ka vs. S/X

Accuracy tested vs. S/X catalog (GSFC-2008b-astro)

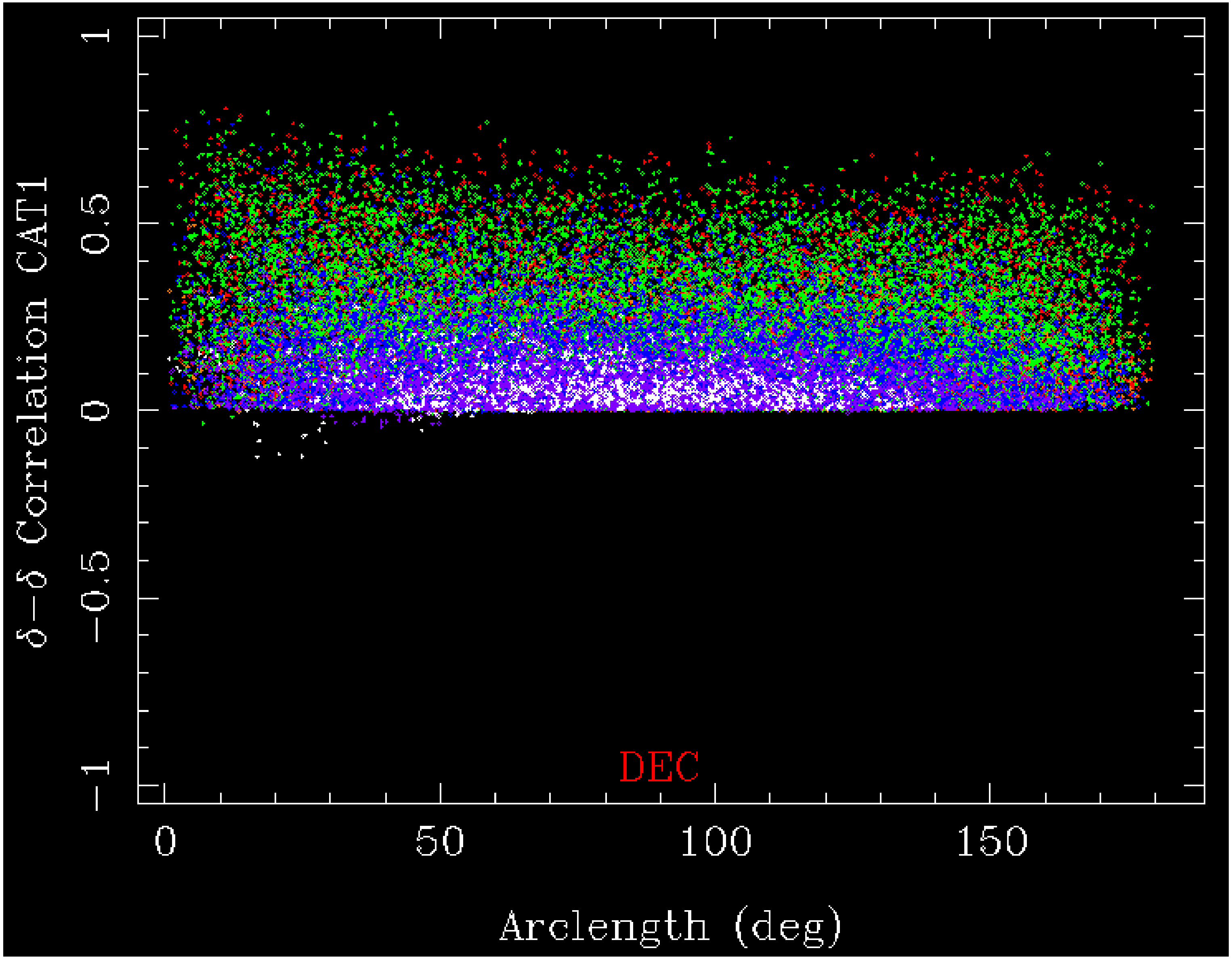




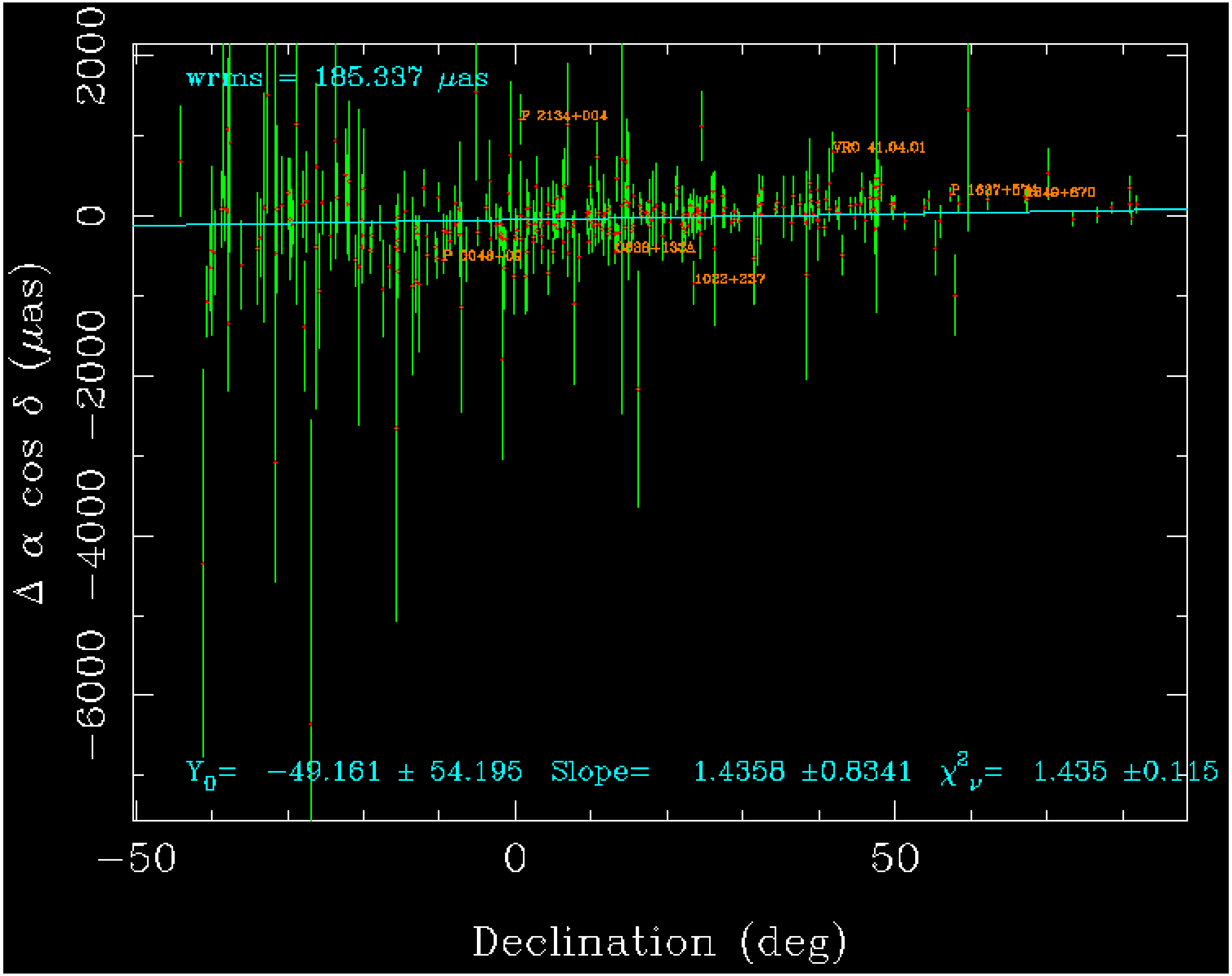
RA: 200 μas = 1.0 nrad

Dec: 280 μas = 1.35 nrad

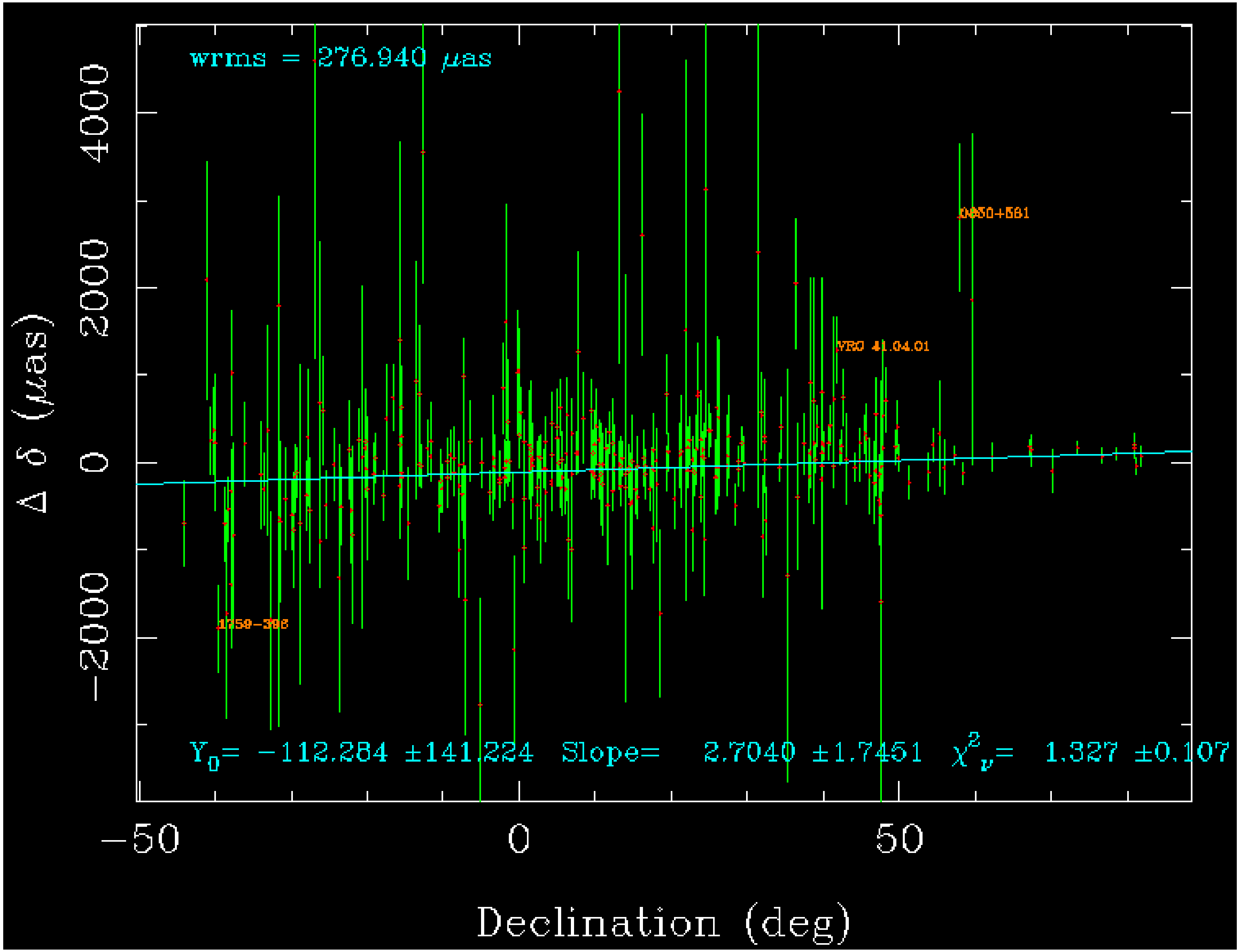
Dec-Dec inter-source correlations



Zonal Errors: ΔRA vs. Dec

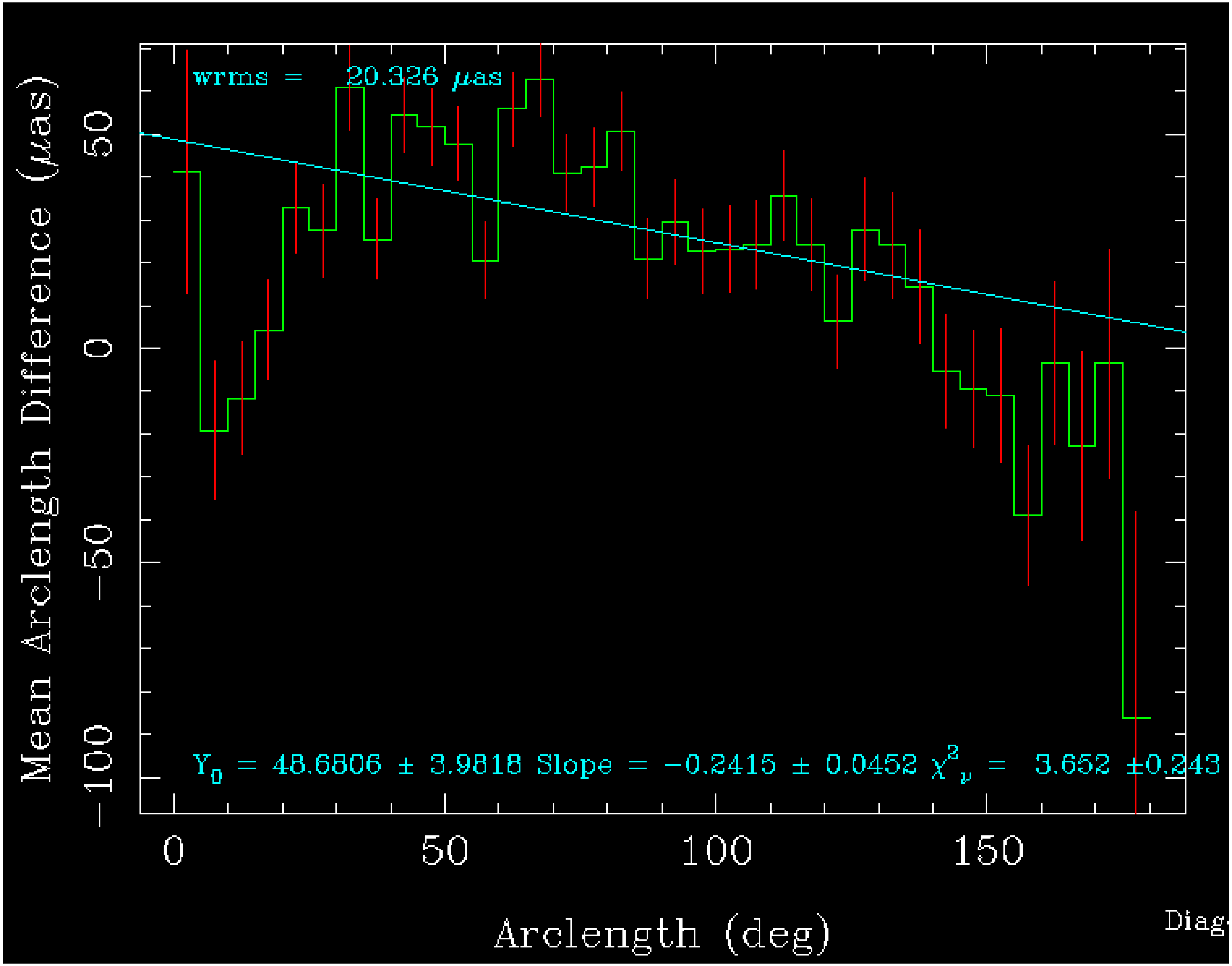


Zonal Errors: ΔDec vs. Dec



Slope 1.55 sig

Zonal Errors: Δ arc vs. arc



Results limited by Ka-band SNR

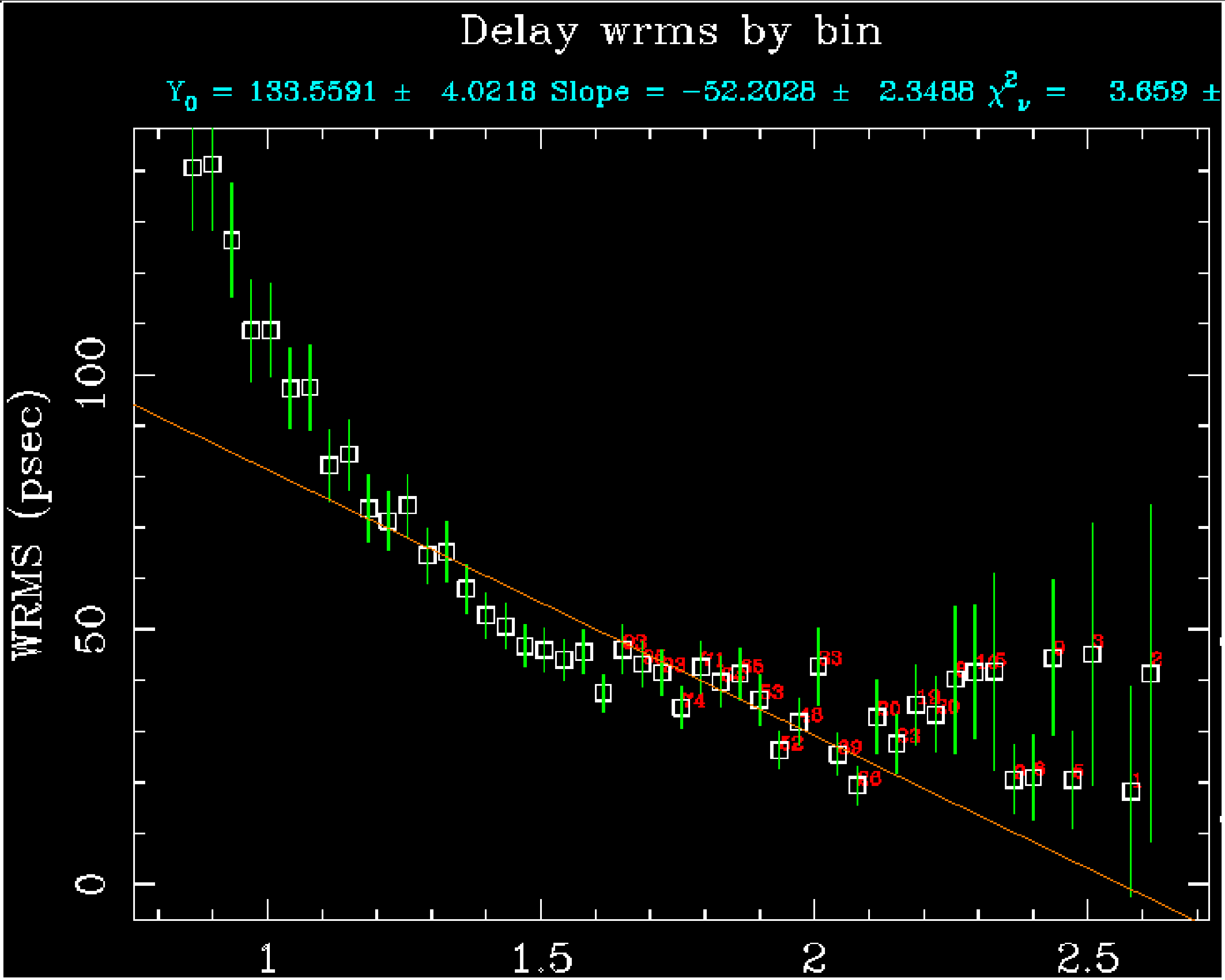
Solution:

1) More bits

Mk5-A: Gbps
3X SNR increase

2) Ka pointing

Potential for
50% increase
in SNR from
Improved pointing
calibrations



log10(SNR(Ka))

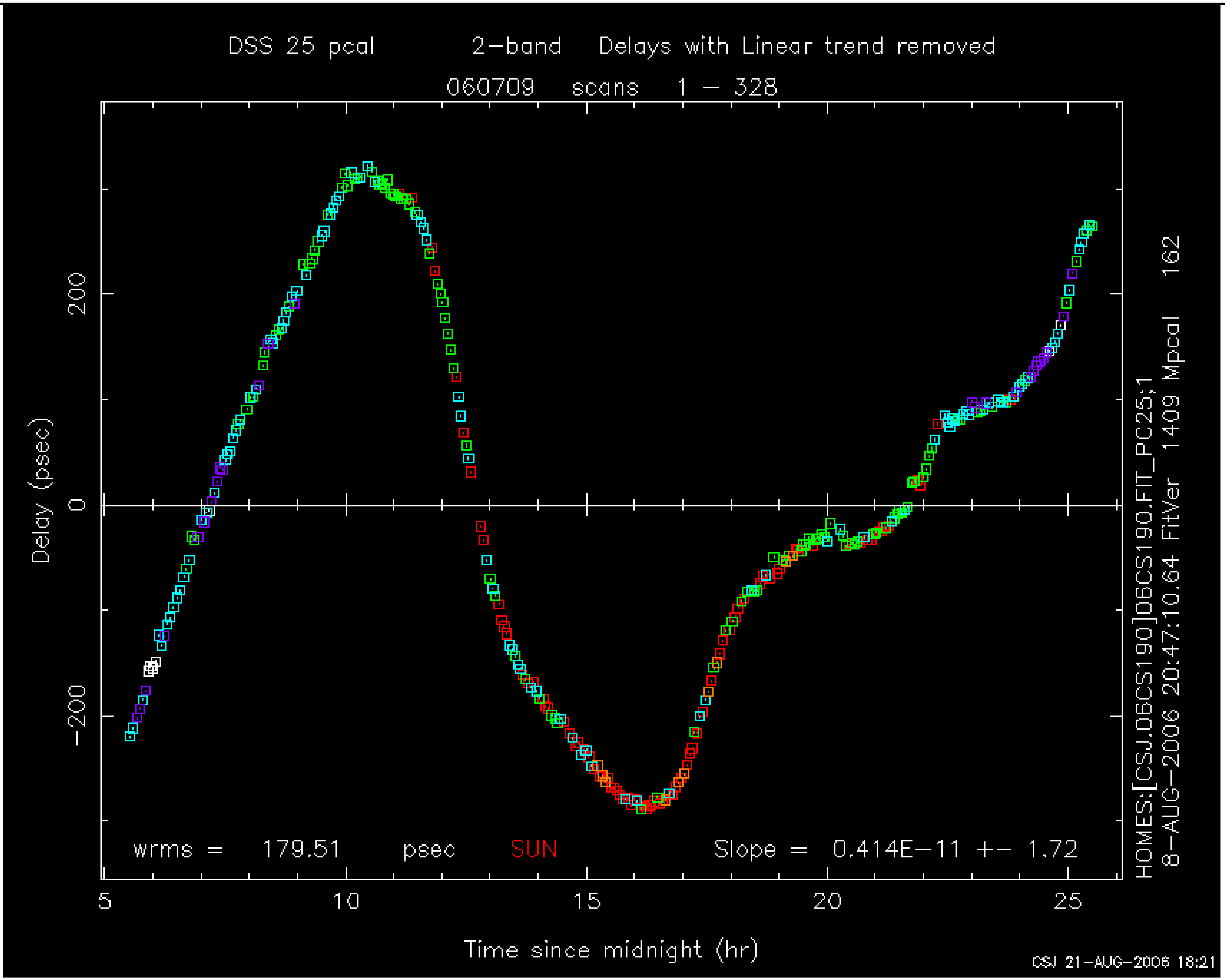
Results limited by No Ka-band Phase cal

Problem:
180 psec ~diurnal effect

Solution:

Ka-band Phasecal Prototype Demo'd --- >

Operations ~2010



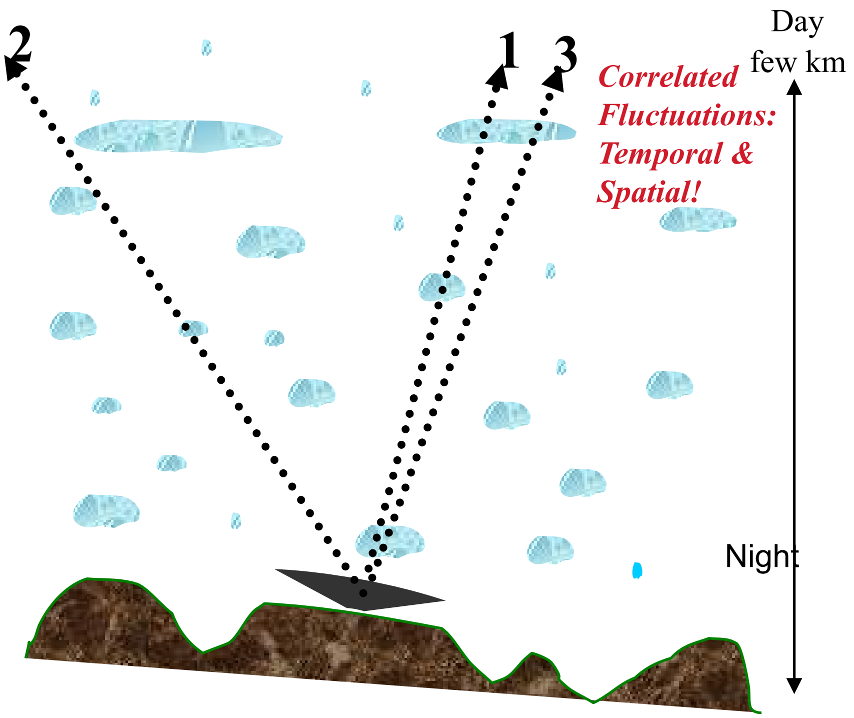
Troposphere Solution 1: Better Estimation

- Modify Least Squares to account for observation correlations -- both temporal and *spatial*

- Use Kolmogorov frozen flow model of Treuhaft & Lanyi (Radio Sci. 1987)

- This model increases the information available to the estimation process
  thereby enabling both
  1) Reduced parameter biases
  2) Reduced parameter sigmas

- Validation: Improves agreement of X/Ka vs. S/X catalogs by about 10% in Declinations (less in RA)



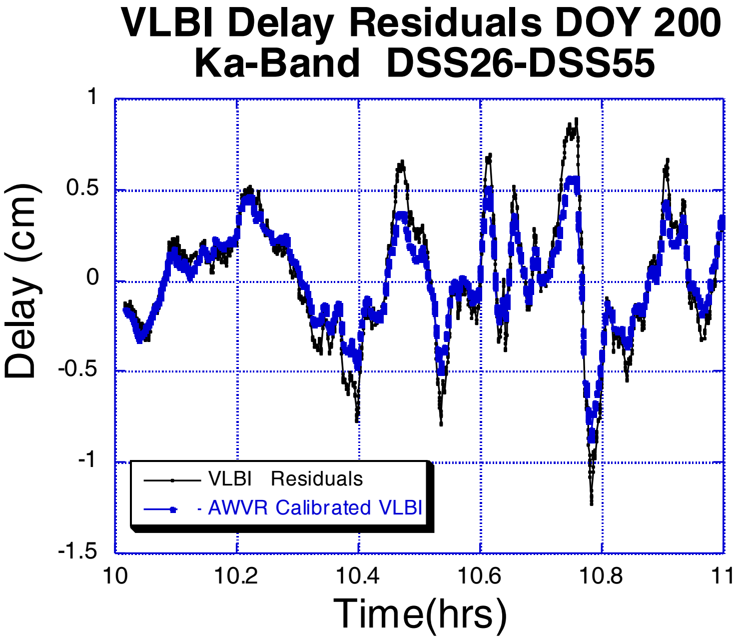
Troposphere Solution 2: Better Calibration

- JPL Advanced Water Vapor Radiometer
  ~ 1 deg beam better matches VLBI
  improved gain stability
  improved conversion of brightness
  temperature to path delay

- Initial demos show 1mm accuracy
  Goldstone-Madrid 8000 km baseline
  using X/Ka phase delays
  (Jacobs *et al*, AAS Winter 2005).

- A-WVRs deployed at Goldstone & Madrid
  Seeking funding for Tidbinbilla, Australia

- A-WVR not used yet for X/Ka catalog



X/Ka Summary

- ***ICRF now extended to X/Ka-band with ~1/4 mas accuracy!***

Caveat: models & cals still rely on S/X; still need S/X!

Observations: X/Ka-band (8.4/32 GHz) MkIV:

41 sessions DSN-34m of ~24 hours each

328 sources north of -45 Dec

Sources unevenly observed

Accuracy currently SNR limited: 312 common sources -

ΔRA ~ 200 μas wRMS (1.0 nrad)

ΔDec ~ 280 μas wRMS (1.35 nrad)

Zonals ~ 50 μas (0.25 nrad)

- ***Future Plans:*** ***potential for better than 100 μas accuracy***

SNR: Mk-5A Gbps allows 3X sensitivity increase

better pointing has potential for 50% better SNR

Instrumentation: Ka-band phase cal scheduled for ~2010

Trop: Estimation using observation spatial/temporal correlations

Calibration using Advanced Water Vapor Radiometer